

## Physical Characteristics of Alkaline Stabilized Sewage Sludge (N-Viro Soil) and Their Effects on Soil Physical Properties

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### ABSTRACT

The N-Viro process for alkaline stabilization of municipal sewage sludge combines dewatered sludge with one or more alkaline industrial byproducts and destroys pathogens by a combination of high pH, heat, and drying. The final product, N-Viro Soil, is a soil-like material that is being used as an agricultural lime substitute, soil amendment, and soil substitute. Physical characteristics of 28 N-Viro Soils were determined and compared to those of mineral soils. The N-Viro Soils have an average solids content of 62%, particle density of 1.96 Mg/m<sup>3</sup>, bulk density of 0.59 Mg/m<sup>3</sup>, and total porosity of 70%. Mean moisture retention was 66, 58, 34, and 31% (v/v) at saturation, 5.9, 33, and 1.5 MPa, respectively. Available water content was 27% by volume (60 cm water tension, 1.5 MPa). Noncompacted and compacted saturated hydraulic conductivities were high,  $3 \times 10^{-2}$  and  $9 \times 10^{-4}$  cm/s, respectively. Mean weight diameter (MWD) of water stable aggregates was 2.0 mm. Fifty-six percent of the materials were >2 mm in diam., almost all of this (88%) in sizes <16 mm. Of the <2-mm fraction, 69% was >0.5 mm. The N-Viro Soils have a shrinkage of 58%, and Atterberg liquid limit, plastic limit, and plasticity index of 76, 64, and 18% water (w/w), respectively. The N-Viro Soils are similar in physical attributes to those of medium to fine textured, porous soils with granular, stable aggregates, and nonplastic consistency. The moisture retention characteristics are those of a fine textured soil dominated by fine pores and low to medium available water holding capacity, and these materials are highly permeable, even when compacted. N-Viro Soil was applied to the Miamian silt loam (fine, mixed, mesic Typic Hapludalf) in the field at a rate of 500 Mg/ha (dry solids), and changes in physical properties were measured 1 yr after application. All effects of N-Viro Soil were statistically significant ( $P = 0.01$ ), except total porosity, 33 KPa moisture holding capacity, 0.5- to 0.25-mm water stable aggregates, and pocket penetrometer measurements, and all of the effects were beneficial.

SINCE THE ADVENT of nationwide advanced wastewater treatment in the late 1960s in the USA, much attention has been placed on treatment and disposal or use of the residual solids of wastewater processing. Those solids, referred to as sewage sludge, and more recently biosolids, have traditionally been placed in municipal landfills, incinerated, ocean dumped, or applied to agricultural land. Lesser amounts have been used for reclamation of disturbed lands, and given away or sold for gardening or commercial horticulture. Before the 1980s, most sludge was biologically digested as a means of stabilizing the sludge organics and to reduce pathogens. In the 1980s, more advanced technologies for sludge treatment emerged that produced a pathogen-free product

and stabilized sludge organic matter. The two most widely used approaches are biological composting and alkaline stabilization. While composting relies on biological degradation, heat, and drying to kill pathogens and stabilize sludge organic matter, alkaline stabilization utilizes a combination of high pH, heat, and drying to achieve the same purpose. One of the alkaline stabilization technologies is the patented N-Viro Process. This process involves the mixing of partially dewatered sewage sludge (either digested, waste activated, or raw primary-waste activated) with an alkaline material or blend of materials. Solids content of the sludge can vary from 15 to 40% (Logan and Burnham, 1992), and a number of industrial by-products can be used as alkaline reagents. These include cement kiln dust, lime kiln dust, lime (CaO), limestone, alkaline fly ash, FGD, other coal burning ashes, and wood ash. The reagents are used alone or in combination (referred to as alkaline admixture, AA), according to local availability and cost, so as to provide pH in the sludge-AA mixture >12, temperatures between 52 and 62°C, and solids content >50% for 12 h. The pH must then remain >12 for at least 3 d (Burnham et al., 1992). At this point, the final product has achieved the USEPA's classification for complete pathogen destruction (USEPA, 1993). The material must be further dried, however, by windrowing to at least 60% solids to produce a uniform, granular product if it is to be used beneficially. The material is usually windrowed a minimum of three times during a period of 3 to 7 d. At this point, the material, if it also meets the federal sludge concentration limits for trace elements, and the vector attraction requirements (USEPA, 1993), can carry the trademark N-Viro Soil. There are >30 operating N-Viro facilities in the USA, Australia, and England; and N-Viro Soil is used as a substitute for agricultural limestone, as a fertilizer, for land reclamation, as a soil amendment for landscaping, as an ingredient with other materials for the manufacture of synthetic topsoil, and as a substitute for soil for landfill cover (Logan, 1992; Logan and Burnham, 1992; Pierzynski and Schwab, 1993). N-Viro Soil has been previously characterized for lime, nutrient and trace element characteristics (Logan, 1992; Logan and Burnham, 1992; Logan and Harrison, 1993), but no study has been made of the physical properties of these materials. Physical data is essential if these materials are to be used effectively as substitutes for soil in various applications.

A study of 28 N-Viro Soil materials from various operating facilities in the USA, England, and Australia

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**Abbreviations:** FGD, flue gas desulfurization; MWD, mean weight diameter; AA, alkaline admixture; CKD, cement kiln dust; LKD, lime kiln dust; RPD, relative percent difference.

Table 1. Alkaline admixture type and dose rate, and sludge type for 28 N-Viro soils in the study.

No.	N-Viro Soil Location	Alkaline admixture		Sludge type
		Type	Dose rate (%)†	
1	Aged Horsham, England	CKD, LKD‡	30 CKD, 8 LKD	Primary
2	Bowling Green, KY	CKD		Digested
3	Aged Durham, NC	CKD, LKD	35	Anaerobic
4	Durham, NC	LKD	35	Anaerobic
5	Easley, SC	LKD	40	Aerobic
6	Toledo, OH	FGD		Anaerobic, lime treated (8%)
7	Buckland, England	CKD, LKD	40 CKD, 7 LKD	Primary
8	East Hyde, England	CKD, LKD	45 CKD, 3 LKD	Primary & activated
9	Horsham, England	CKD, LKD	30 CKD, 8 LKD	Primary
10	Greenville, SC	CKD, LKD	45	Raw secondary
11	Phillipsburg, NJ	LKD	60 LKD, 4 CaO	Aerobic & anaerobic
12	Jeffersonville, IN	LKD	30-35	Aerobic
13	Kent County, DE	CKD	65 CKD, 8 CaO	Aerobic
14	Knox County, TN	LKD	50	Raw secondary
15	Lexington, KY	CKD		Digested
16	Clyde, NC	LKD	50	Aerobic
17	Toledo, OH	LKD	40-45	Anaerobic, lime treated (8%)
18	Oakland, CA	Fly ash, CKD	49	Anaerobic
19	Middlesex County, NJ	CKD	52 CKD, 3.5 CaO	Aerobic
20	Sioux City, IA	CKD, LKD, FGD	51, 1 CaO	Anaerobic
21	St Paul, MN	CKD, FGD	33	Primary & activated
22	Sydney, Australia (Brown)	CKD	30 CKD, 4 CaO	Primary
23	Sydney, Australia (Gray)	CKD	30 CKD, 4 CaO	Primary
24	Tomball, TX	CKD	30	Aerobic
25	Troy, IL	CKD	45-50	Primary & secondary
26	Syracuse, NY	CKD, LKD	63	Anaerobic
27	Jupiter, FL	CKD	50 CKD, 11 CaO	Activated
28	Tarpon Springs, FL	CKD	43 CKD, 10 CaO	Activated

† Percentage of sludge cake by wt.; sludge cake solids content varies from ~14 to 40% (w/w).

‡ CKD = cement kiln dust; LKD = lime kiln dust; FGD = flue gas desulfurization bed ash.

was initiated in 1992 to develop baseline characteristics of N-Viro Soil materials that would reflect differences in process variables such as sludge type and quality, type and dose rate of AA, and age of the material. The alkaline materials are selected to provide the following characteristics: a source of CaO to raise pH and produce heat by exothermic hydrolysis to Ca(OH)<sub>2</sub>; odor adsorption, and accelerated drying. The initial alkaline ingredient used in the N-Viro process was cement kiln dust (CKD) (Burnham et al., 1992), but a combination of alkaline materials are now used that include lime kiln dust (LKD), FGD by-product, fly ash, fluidized bed ash, and wood ash. Of the 28 N-viro Soils used in the study, those from Toledo, OH, were made with either LKD or FGD by-product, while the Oakland, CA, N-Viro Soil was made with alkaline fly ash. The other 25 materials were made with CKD or mixtures of CKD and other alkaline reagents, such as lime (CaO) or various combustion ashes such as fluidized bed ash (Table 1). Several of the materials (Tomball, TX; Sydney, Australia; and Durham, NC) had been aged by extended windrowing or by extended storage, while the majority were freshly made. These materials were studied as received and variability in their properties reflects the range of operating conditions to be found at the >30 N-Viro facilities worldwide. Information on sludge type, AA type and dose rate, and age of the N-Viro Soil were provided by each operator.

## METHODS AND MATERIALS

### Physical Properties of N-Viro Soils

Samples were shipped from the various facilities without preservation in sealed containers. Samples ranged in size from

<1 kg to several kilograms. They were stored at 4°C until they were analyzed. Physical properties determined included: solids, particle and bulk densities, total porosity, particle-size distribution, moisture retention at 0, 5.9, 33, and 1.5 MPa tensions, saturated hydraulic conductivity, aggregate stability, Atterberg Limits, and shrinkage. In addition, samples were compacted using a standard Proctor procedure (ASTM, 1992a) and reanalyzed for bulk density and saturated hydraulic conductivity. Standard methods published by ASTM and the Soil Science Society of America were used unless specified. All analyses were performed in duplicate. A few of the N-Viro Soils were received in insufficient quantity to perform all analyses. All analyses are reported on a dry solids basis except solids content itself.

Soil physical characterization data are also presented for four Ohio mineral soils for comparison. These soils had been selected for a separate study and the characterizations were performed at a different time from that of the N-Viro Soils; however, identical methods and equipment were used in both cases. The soils were selected to give a range in texture and structure and included: Miamian silt loam, Kokomo silty clay loam, (fine, mixed, mesic Typic Argiaquoll) the B<sub>2</sub> horizon of a Paulding clay (very-fine, illitic, nonacid, mesic Typic Haplaquept); and the B<sub>2</sub> horizon of a Hazleton sandy loam (loamy-skeletal, mixed, mesic Typic Dystrochrept).

Chemical characteristics of the 28 N-Viro Soils in the survey are reported elsewhere (Logan and Harrison, 1993) and are summarized in Table 2. These materials have a high acid neutralizing capacity in the form of CaCO<sub>3</sub> and Ca(OH)<sub>2</sub> (Logan, 1993) and a high pH. They have ≈1% each of total N, P, and K, and are low in metals compared with most sewage sludges. In order to carry the N-Viro Soil trademark, they must meet the USEPA pollutant concentration limits for 10 trace elements.

**Table 2. Summary of chemical properties of the 28 N-Viro Soils (Logan and Harrison, 1993).**

Parameter	Maximum	Minimum	Mean
pH	12.8	7.24	11.9
Electrical conductivity (dS/m)	15	3	9
Total (%)			
C	20.6	5.6	12.1
N	1.93	0.22	0.89
P	1.14	0.21	0.41
Na	0.59	0.06	0.18
K	4.31	0.09	1.26
Mg	9.45	0.20	1.00
Ca	39.8	10.5	25.0
CCE†	77	18	53
Total (mg/kg)			
As	35.8	2.4	7.6
Cd	4.02	<0.01	0.83
Cu	294	43	134
Mo	3.45	0.02	1.38
Ni	563	6.6	55
Pb	452	<0.01	48
Se	3.67	0.58	1.69
Zn	426	39	186

† Calcium carbonate equivalent.

### Solids

A sample ( $\approx 2$  g) was accurately weighed into a metal cup and oven dried overnight at 105°C. Solids content was calculated as a percentage of total sample weight. Solids content is the parameter normally used in the wastewater industry rather than moisture content, but one can be easily derived from the other. There was no significant loss of N-Viro Soil mass with drying at this temperature. Total organic content averages 12% by weight (Table 2) and volatile solids are low. Volatile solids are reduced in the N-Viro process by the combination of temperature (52–62°C) and accelerated drying.

### Particle Density

A modified pycnometer method was used (Blake and Hartge, 1986a). Weighed samples ( $\approx 50$  g) were placed in weighed 100-mL volumetric flasks; water was added to volume and the flasks weighed again. Temperature was recorded to obtain water density and the volume of water displaced by the sample was used to calculate particle density.

### Bulk Density

Weighed stainless steel cylinders ( $\approx 50$  mm in diam. and 51 mm in height) were used for bulk density (Blake and Hartge, 1986b), moisture retention, and saturated hydraulic conductivity. Cheese cloth was placed on one end of each cylinder and held in place with rubber bands. Samples were packed into the cylinders by filling about one-third full, tamping (10 tamps with a fixed drop of 4 cm) and refilling with sample until full. The filled cylinders were weighed and bulk density calculated as oven-dry corrected weight divided by cylinder volume. The same procedure was used to determine bulk densities of compacted cores (see below).

### Total Porosity

Total porosity is calculated from particle and bulk densities by (Danielson and Sutherland, 1986):

$$\text{Porosity (\% by volume)} = (1 - \text{BD/PD}) \times 100$$

### Moisture Retention

Low matric potential moisture retention capacities (0 cm and 5.9 KPa) were determined (Klute, 1986) using a tension table by placing preweighed saturated cores on top of EXCO porous plastic from FMC Corporation (Pine Brook, NJ), a material that is water-permeable, but not air permeable. The desired pressure was then set and the samples were left overnight and weighed to determine the amount of water retained in the sample.

High matric potential moisture retention capacities (33 KPa and 1.5 MPa) were obtained using extractors. The preweighed saturated cores were placed on saturated ceramic plates that are specific to the desired pressure. Nitrogen gas or air was used to displace first the air and then the water in the cores by forcing the water through the plates. The samples were left in the extractor overnight and then weighed to determine the amount of moisture retained.

### Saturated Hydraulic Conductivity

The packed cylinders used for the bulk density determination were used to determine  $K_s$  by a constant head technique (Klute and Dirksen, 1986). An identical cylinder was attached to the open end with duct tape to act as a reservoir for the hydraulic head. The other end of the assembly, covered with cheese cloth to retain solids, was placed on a Buchner funnel to collect leachate. Water was added to the reservoir and flow adjusted so as to maintain a constant head. Leachate volume was measured over timed periods until flow was essentially constant at which time the final flow rate was determined.  $K_s$  was determined from the formula:

$$K_s = \frac{\text{Vol. of water (mL)} \times \text{Height of core (cm)}}{\text{Cross sectional area of sample (cm}^2\text{)} \times \text{Time(s)} \times \text{Hydraulic gradient (cm)}}$$

### Compacted Saturated Hydraulic Conductivity

A core was completely filled with the sample and then a rubber stopper with a diameter equivalent to that of the core was placed on top of the sample (ASTM, 1992a). A rammer was used to compact the soil by allowing it to fall on the stopper and soil 25 times. The core was again filled with the sample and this process repeated until the compacted sample was even with the top of the core. The same method described above for determining  $K_s$  values for the packed cores was used to determine  $K_s$  values for the compacted cores.

### Aggregate Stability

A known amount of air-dried soil was placed in the uppermost sieve (5 mm) of the mechanical agitator (Kemper and Rosenau, 1986). The agitator was then started and the sample and sieves (5 mm, 2 mm, 1 mm, 0.5 mm, and 0.25 mm) were repeatedly raised and lowered, while completely submerged in water for  $\approx 30$  min. The contents of each sieve were then carefully transferred to a preweighed beaker and oven dried overnight at 105°C. The contents of each beaker were then weighed to determine the fraction of the sample that remained in each sieve. Results were used to calculate the MWD of the aggregates (Kemper and Rosenau, 1986).

### Atterberg Limits and Shrinkage

N-Viro Soils, although well aggregated, contain colloidal materials in the form of sludge organic matter and clays from the CKD. They have been observed to exhibit plastic behavior when wet. The Liquid Limit, Plastic Limit, and Plasticity Index Atterberg Limits were determined by standard ASTM procedures (ASTM, 1992c).

Shrinkage was measured by placing a semifluid paste of the sample in a lightly oiled (with Vaseline) shrinkage dish with a known volume by repeatedly placing one-third of the sample in the dish and then tapping the dish 10 times to remove any air bubbles. The surface of the dish was then leveled and the dish and sample were weighed. The sample was first air dried and then oven dried to avoid cracking. The weight of the dried sample was recorded along with the width and diameter of the dried soil pat. The shrinkage limit was then determined from the formula:

$$S = M(\%) - [\rho_{\text{water}} \times \frac{V_{\text{wet}} - V_{\text{dry}}}{W_{\text{dry}}} \times 100]$$

where  $M(\%)$  = moisture content of wet soil by weight

$V_{\text{wet}}$  = volume of wet soil pat ( $\text{m}^3$ )

$V_{\text{dry}}$  = volume of dry soil pat ( $\text{m}^3$ )

$W_{\text{dry}}$  = weight of dry soil pat (Mg)

$\rho_{\text{water}}$  = density of water ( $\text{Mg}/\text{m}^3$ )

### Particle-Size Analysis

Weighed samples (>10 g) were sieved into the following classes (mm): >32, 32 to 25.4, 25.4 to 19, 19 to 16, 16 to 6.35, 6.35 to 4.7, 4.7 to 2, and <2 (ASTM, 1992b); 10-g samples of the <2-mm fraction were further sieved into the following classes (mm): 2 to 1, 1 to 0.5, 0.5 to 0.25, 0.25 to 0.1, 0.1 to 0.074, 0.074 to 0.05, and <0.05. Attempts to further fractionate the <0.05-mm fraction into clay-sized (<2  $\mu\text{m}$ ) fraction by Stoke's sedimentation were unsuccessful because the sample could not be dispersed with standard dispersants such as Na hexametaphosphate (Calgon) or ultrasonic probe. This was because of the very high Ca content of the N-Viro Soils.

### Data Analysis

All analyses were performed on duplicate samples except for Atterberg Limits and particle-size distribution for which there was only enough sample for a single analysis. All analyses were not performed on some samples because of the limited sample size received. Variation within a sample was expressed as relative percent difference (RPD), defined as:

$$\text{RPD}(\%) = \frac{(X_1 - X_2)}{(X_1 + X_2)/2} \times 100$$

Overall means and standard deviations were determined across the 28 N-Viro Soils.

### Effects of N-Viro Soil on Physical Properties of Mineral Soil

An N-Viro Soil, processed with anaerobically digested sludge from Columbus, OH, as part of a pilot study, was applied at a rate of 500 Mg/ha (dry solids) to Miamian silt loam in the field at Ohio State University Agronomy Farm in Columbus on 30 July 1992. This was one of the four mineral

soils used in the N-Viro Soil characterization component of the study. The site is part of a larger field study of land applied organic wastes. The N-Viro Soil was applied by hand to the surface of the plot and mixed into the top 15 cm by rototilling. The plots are 5 m by 5 m and separated from each other by a grassed 5-m buffer. Each plot is enclosed by a plywood perimeter placed 45 cm into the soil and with a 45-cm freeboard. The site has been in general agriculture for at least 100 yr, and as a research farm for at least 30 yr. The soils in this area are badly eroded with most of the original  $A_1$  eroded to expose the  $B_2$ . The two control plots from the larger study are within 50 m of the treated plots and are used here as controls. The control soil has a 1:1 water pH of 6.5, and contains  $\approx 15$  g/kg organic C. Surface crusts form readily following spring and summer rains. Samples of the Columbus N-Viro Soil were characterized for the same physical properties as in the characterization component of the study. Composite soil samples from the control and treated plots (0-15 cm) were taken on 20 July 1993,  $\approx 1$  yr after application of the N-Viro Soil, and were analyzed for the same physical properties as for the N-Viro Soil. In addition, measurements of compaction were made in the field at the time of soil sampling with a pocket penetrometer.

## RESULTS

### Physical Properties of N-Viro Soils

#### Solids

Solids content ranged from 46 to 75% by weight with an average value of  $\approx 60\%$  (Table 3). This conforms well with the process parameters required for N-Viro Soil. The initial sludge-AA mix must have a solids content of 50% and the final product should be in the range 60 to 65% to have maximum granularity and yet not produce dust. Only one replicate value on one material had solids content less than the 50% required for the N-Viro process.

#### Particle Density

Particle density of N-Viro Soil represents an average of the densities of the two component materials, sludge and the AA. Sludges typically have densities of  $\approx 0.5$  to  $1.0$   $\text{Mg}/\text{m}^3$ , while AA materials will have densities of  $\approx 2.2$  to  $3.3$   $\text{Mg}/\text{m}^3$  ( $\text{CaCO}_3$ ,  $2.93$   $\text{Mg}/\text{m}^3$ ;  $\text{CaO}$ ,  $3.3$   $\text{Mg}/\text{m}^3$ ;  $\text{Ca}(\text{OH})_2$ ,  $2.24$   $\text{Mg}/\text{m}^3$ ; Weast and Astle, 1980). N-Viro Soils have particle densities that fall between the values for sludge and AA, ranging from  $1.6$  to  $2.4$   $\text{Mg}/\text{m}^3$  (Table 3). Average values were  $\approx 1.9$   $\text{Mg}/\text{m}^3$ . The high and low values corresponded to those materials with the highest and lowest solids contents (Table 3) and probably reflects the AA-sludge ratio. Soils typically have particle densities of  $2.5$  to  $2.8$   $\text{Mg}/\text{m}^3$  (Baver, 1956), and those of the four soils used for comparison fall in this range (Table 3).

#### Bulk Density

Bulk density was determined from loosely packed cores and values ranged from  $0.4$  to  $0.8$   $\text{Mg}/\text{m}^3$  (Table 3). The high and low values corresponded to the particle-density values (see above), suggesting that density of the primary particles rather than differences in structure

**Table 3. Solids, particle density, bulk density, and total porosity in 28 N-Viro Soils and four selected mineral soils. Mean of duplicate analyses.**

No.	Location	Solids		Particle density		Bulk density		Porosity	
		(%)	RPD†	(Mg/m <sup>3</sup> )	RPD†	(Mg/m <sup>3</sup> )	RPD†	(%)	RPD†
1	Aged Horsham, England	60	0	1.92	0.04	0.54	0.05	72.0	1.29
2	Bowling Green, KY	60	0	1.79	0.03	0.47	11.01	73.9	2.88
3	Aged Durham, NC	78	1	2.41	0.01	0.84	3.68	65.3	0.53
4	Durham, NC	69	1	2.12	0.03	0.72	2.57	65.9	1.69
5	Easley, SC	56	2	1.83	0.00	0.56	2.45	69.6	0.44
6	Toledo, OH (FGD)	56	0	1.87	0.00	0.51	6.83	72.6	1.26
7	Buckland, England	60	5	1.92	0.01	0.55	2.01	71.2	0.03
8	East Hyde, England	65	3	2.07	0.03	0.60	1.04	71.0	1.17
9	Horsham, England	62	3	1.96	0.04	0.52	8.10	73.7	0.44
10	Greenville, SC	68	0	1.96	0.04	0.58	11.97	70.3	1.40
11	Phillipsburg, NJ	63	1	1.99	0.03	0.63	0.86	68.5	1.18
12	Jeffersonville, IN	69	1	2.00	0.00	0.68	15.40	66.0	3.88
13	Kent County, DE	71	3	2.26	0.05	0.79	7.67	65.1	0.42
14	Knox County, TN	70	3	2.00	0.05	0.71	5.60	64.6	3.54
15	Lexington, KY	50	1	1.76	0.01	0.47	7.37	73.1	1.17
16	Clyde, NC	62	1	2.11	0.01	0.61	29.83	71.4	6.20
17	Toledo, OH (LKD)	61	1	1.95	0.01	0.61	1.51	68.7	0.01
18	Oakland, CA	50	1	1.63	0.04	0.40	13.68	75.4	1.08
19	Middlesex County, NJ	56	2	1.86	0.01	0.55	1.02	70.3	0.14
20	Sioux City, IA	60	2	1.99	0.04	0.59	1.44	70.5	1.36
21	St. Paul, MN	62	1	1.95	0.03	0.54	1.48	72.3	0.47
22	Sydney, Australia (Brown)	62	2	2.02	0.06	0.57	2.91	71.9	1.04
23	Sydney, Australia (Gray)	46	4	1.56	0.02	0.38	0.10	75.8	0.46
24	Tomball, TX	78	0	2.27	0.05	0.80	0.42	64.8	1.57
25	Troy, IL	66	1	2.06	0.07	0.62	1.36	69.7	2.30
26	Syracuse, NY	51	1	1.77	0.00	0.47	4.01	73.7	0.71
27	Jupiter, FL	68	2	1.84	0.00	0.66	1.29	64.1	0.39
28	Tarpon Springs, FL	68	2	1.96	0.00	0.65	5.48	66.9	1.41
	Overall mean	62		1.96		0.59		69.9	
	Overall SD	8		0.18		0.11		3.46	
	Hazleton sandy loam	—	—	2.68	—	1.62	—	40	—
	Kokomo silty clay loam	—	—	2.62	—	1.16	—	56	—
	Miamian silt loam	—	—	2.65	—	1.32	—	50	—
	Paulding clay	—	—	2.60	—	1.12	—	57	—

† Relative percent difference.

were responsible for the observed bulk density values. Mineral soils typically have bulk densities of 1.2 to 1.8 Mg/m<sup>3</sup> (Brady, 1984), and those of the four comparison soils ranged from 1.1 Mg/m<sup>3</sup> in the highly structured clay to 1.62 Mg/m<sup>3</sup> in the structureless sand (Table 3).

### Total Porosity

The N-Viro Soils had high porosities, ranging from 64 to 75% (Table 3). This, with the lower particle density, contributes to the low bulk densities of these materials. The high total porosity is a consequence of the intra aggregate porosity formed by the flocculation of colloidal sludge organic matter with Ca in the alkaline reagents, and interaggregate porosity created by the granulation that occurs during windrowing. The high total porosity makes it an excellent material for root growth and for soil drainage. Typical soils have porosities of 30 to 60% (Brady, 1984). The four comparison soils had porosities ranging from 57% in the structured clay to 40% in the structureless sand (Table 3).

### Moisture Retention Capacity

Saturated water content (given as volume content of water per unit volume of N-Viro Soil) ranged from 47 to 75% and corresponded closely to total porosity (Table 4). The 5.9 KPa content, often found in soils after gravity drainage has occurred following a rain, and representing

air-filled porosity, was on average only 0.08% water by volume less than the saturated water content (Table 4), somewhat lower than observed for the four mineral soils. There was significantly lower water content at 33 KPa compared with 5.9 KPa (Table 4), indicating that a high percentage of the water held by N-Viro Soil is in medium sized pores. The 1.5 MPa water content was high, 50% or more of the total water holding capacity (Table 4), and reflects the high hygroscopic water content of sludge organic matter and of the AA. Cement kiln dust in particular is fine grained, with >75% passing a 75- $\mu$ m sieve (Burnham et al., 1992), and has a relatively high specific surface area. We measured surface area of selected cement kiln dusts of  $\approx$ 2000 m<sup>2</sup>/kg, in the range of that of silt sized particles (Jury et al., 1991). Epstein (1975) reported gravimetric moisture content of digested sewage sludge of  $\approx$ 180%, which would correspond to a volumetric water content of  $\approx$ 90%, assuming a bulk density of sludge of  $\approx$ 0.5 Mg/m<sup>3</sup>. The addition of AA would have lowered this value in the N-Viro Soils. The corresponding 1.5 MPa moisture content of digested sludge (Epstein, 1975) is  $\approx$ 60% by volume, comparable to the values determined for the N-Viro Soils. The available water content (defined as the difference in the 5.9 KPa and 1.5 MPa water contents) of the N-Viro Soils ranged from 14 to 40% by volume, with a mean of 27% (Table 4). The moisture contents across the range of suction pressures studied are similar to those of well

**Table 4. Moisture retention capacity at saturation (5.9, 33, and 1.5 MPa) and available water holding capacity in 28 N-Viro Soils and four selected mineral soils. Mean of duplicate analyses.**

No.	Location	Volumetric moisture content (mL water/cm <sup>3</sup> soil)									
		Saturation		5.9 KPa		33 KPa		1.5 MPa		Available water	
		Mean	RPD†	Mean	RPD†	Mean	RPD†	Mean	RPD†	Mean	RPD†
1	Aged Horsham, England	0.68	6	0.57	12	0.29	10	0.22	4	0.34	23
2	Bowling Green, KY	0.73	9	0.66	9	0.34	10	0.31	10	0.36	24
3	Aged Durham, NC	0.47	14	0.44	20	0.30	20	0.23	16	0.20	62
4	Durham, NC	0.65	3	0.59	1	0.32	0	0.32	2	0.28	2
5	Easley, SC	0.76	2	0.70	1	0.40	1	0.40	0	0.30	1
6	Toledo, OH (FGD)	0.72	2	0.55	4	0.38	6	0.38	0	0.18	14
7	Buckland, England	0.59	7	0.42	24	0.31	3	0.28	2	0.14	66
8	East Hyde, England	0.70	7	0.60	1	0.25	1	0.28	12	0.33	8
9	Horsham, England	0.69	12	0.58	10	0.28	12	0.27	11	0.30	8
10	Greenville, SC	0.72	1	0.69	1	0.39	4	0.29	6	0.40	7
11	Phillipsburg, NJ	0.63	4	0.50	12	0.31	6	0.30	9	0.20	17
12	Jeffersonville, IN	0.67	4	0.62	9	0.31	0	0.28	5	0.33	14
13	Kent County, DE	0.64	0	0.58	4	0.30	6	0.35	3	0.23	16
14	Knox County, TN	0.64	4	0.59	0	0.31	5	0.33	4	0.26	5
15	Lexington, KY	0.72	5	0.58	27	0.41	6	0.32	6	0.26	52
16	Clyde, NC	0.76	1	0.69	6	0.37	9	0.28	10	0.41	4
17	Toledo, OH (LKD)	0.65	5	0.58	3	0.35	3	0.39	12	0.18	19
18	Oakland, CA	0.71	5	0.54	30	0.39	12	0.31	3	0.22	68
19	Middlesex County, NJ	0.69	3	0.61	2	0.37	3	0.34	37	0.28	40
20	Sioux City, IA	0.70	5	0.60	25	0.37	3	0.37	6	0.23	75
21	St. Paul, MN	0.71	0	0.63	2	0.29	4	0.28	4	0.35	1
22	Sydney, Australia (Brown)	0.65	6	0.56	3	0.33	6	0.22	0	0.34	4
23	Sydney, Australia (Gray)	0.62	0	0.55	5	0.33	2	0.40	4	0.15	29
24	Tomball, TX	0.64	2	0.58	1	0.39	1	0.25	6	0.33	2
25	Troy, IL	0.70	3	0.63	2	0.35	3	0.30	11	0.33	6
26	Syracuse, NY	0.64	3	0.56	8	0.36	5	0.36	7	0.20	34
27	Jupiter, FL	0.59	2	0.53	0	0.31	2	0.34	0	0.19	1
28	Tarpon Springs, FL	0.53	4	0.49	5	0.32	6	0.32	34	0.17	76
	Overall mean	0.66		0.58		0.34		0.31		0.27	
	Overall SD	0.06		0.07		0.04		0.05		0.08	
	Hazleton sandy loam	0.34	—	0.19	—	0.07	—	0.03	—	0.15	—
	Kokomo silty clay loam	0.52	—	0.40	—	0.34	—	0.21	—	0.52	—
	Miamian silt loam	0.47	—	0.37	—	0.31	—	0.18	—	0.51	—
	Paulding clay	0.57	—	0.48	—	0.44	—	0.30	—	0.57	—

† Relative percent difference.

aggregated soils high in organic matter. In the case of the four soils used for comparison, this would be the clay soil (Table 4). Mean available water content of the N-Viro Soils was higher than that of all of the soils (Table 4).

### Saturated Hydraulic Conductivity

Saturated hydraulic conductivities of noncompacted N-Viro Soil were highly variable, with most RPDs >10% (Table 5). All values were >0.005 cm/s and most were >0.01 cm/s. One N-Viro Soil (23) had such rapid water movement that steady-state measurement could not be made. The high value for the Oakland, CA, material (18) was due to a single replicate value as evidenced by the RPD of 169%. Mean values suggest that uncompacted N-Viro Soil has good internal drainage for plant growth. Reported values for mineral soils are  $10^{-2}$  to  $10^{-3}$  cm/s for sandy soils and  $10^{-4}$  to  $10^{-7}$  cm/s for clayey soils (Hillel, 1980), and the mean N-Viro Soil value of 0.028 cm/s was higher than those of the four comparison soils (Table 5). Saturated hydraulic conductivities of compacted N-Viro Soil ranged from a low of  $5 \times 10^{-7}$  cm/s in one of the England materials (Table 5) to a high of  $2.7 \times 10^{-5}$  cm/s in N-Viro Soil no. 27. These results suggest that N-Viro Soil maintains a high degree of structural stability under compaction forces, an important

attribute when using these materials as topsoil, but it also infers that N-Viro Soil alone cannot be used as compacted fill in modern landfills, where  $K_s$  values  $<10^{-7}$  cm/s are usually required, but can be used as daily cover and final cap material. The high  $K_s$  values of these materials were more related to total porosity than to the extent of the larger pores. Linear regression of  $K_s$  vs. total porosity gave an  $R^2$  value of 0.45, while the pore space between 0 and 5.9 KPa moisture tensions regressed against  $K_s$  only gave an  $R^2$  of 0.27.

### Aggregate Stability

Aggregate stability, as measured by sieving a wetted sample through a nest of sieves of varying pore size, is a measure of the structural stability of soil aggregates against the slaking effect and kinetic energy disruption of moving water. Aggregates retained on sieves of 5 mm, 5 to 2 mm, 2 to 1 mm, 1 to 0.5 mm, 0.5 to 0.25 mm, and <0.25 mm were determined as a fraction of the total sample. A higher proportion of aggregates in the larger sizes indicates greater aggregate stability. N-Viro Soils showed a regular distribution of >5-mm size aggregates, ranging from 5 to 45% of the total sample (Table 6). The next largest size (5–2 mm) also was significant in extent, as was the smallest fraction (<0.25 mm) (Table 6). The other fractions were somewhat smaller. The

**Table 5. Noncompacted and compacted saturated hydraulic conductivity in 28 N-Viro Soils. Mean of duplicate analyses.**

No.	Location	Noncompacted		Compacted	
		(cm/s)	RPD†	(cm/s)	RPD†
1	Aged Horsham, England	0.0570	28.00	3.96E-05	92.15
2	Bowling Green, KY	0.0403	5.63	5.18E-04	15.03
3	Aged Durham, NC	0.0026	32.67	1.51E-04	55.58
4	Durham, NC	0.0249	32.64	1.23E-03	17.85
5	Easley, SC	0.0041	41.96	2.86E-05	36.41
6	Toledo, OH (FGD)	0.0255	20.54	9.73E-04	20.80
7	Buckland, England	0.0276	49.69	1.60E-05	13.85
8	East Hyde, England	0.0376	14.78	1.38E-04	123.18
9	Horsham, England	0.0319	11.62	5.04E-07	200.00
10	Greenville, SC	0.0025	64.73	3.25E-04	25.63
11	Phillipsburg, NJ	0.0078	7.91	3.12E-05	71.82
12	Jeffersonville, IN	0.0103	36.71	2.35E-04	109.02
13	Kent County, DE	0.0149	47.46	1.04E-03	82.06
14	Knox County, TN	0.0054	31.20	—	—
15	Lexington, KY	0.0296	49.14	1.23E-03	9.50
16	Clyde, NC	0.0346	20.71	—	—
17	Toledo, OH (LKD)	0.0098	38.55	1.18E-03	9.90
18	Oakland, CA	0.1937	169.08	1.02E-03	34.39
19	Middlesex County, NJ	0.0317	73.96	—	—
20	Sioux City, IA	0.0141	4.71	7.34E-04	10.08
21	St. Paul, MN	0.0235	38.19	—	—
22	Sydney, Australia (Brown)	0.0167	93.82	1.15E-04	—
23	Sydney, Australia (Gray)	—	—	7.21E-05	—
24	Tomball, TX	0.0071	14.74	1.67E-03	—
25	Troy, IL	0.0122	7.70	4.45E-04	11.92
26	Syracuse, NY	0.0055	—	3.22E-05	90.68
27	Jupiter, FL	0.0046	20.89	2.65E-03	15.09
28	Tarpon Springs, FL	0.0004	18.87	4.86E-05	90.42
	Overall mean	0.0278	—	9.15E-04	—
	Overall SD	0.0490	—	8.26E-04	—
	Hazleton sandy loam	0.0185	—	—	—
	Kokomo silty clay loam	0.0248	—	—	—
	Miamian silt loam	0.0145	—	—	—
	Paulding clay	0.0058	—	—	—

† Relative percent difference.

distribution of aggregate sizes is similar to that found for well-aggregated surface-horizon mineral soils. N-Viro Soils generally had more large aggregates and fewer small aggregates than the four Ohio mineral soils (Table 6), and larger overall aggregation (the total fraction >0.25 mm) than the four Ohio mineral soils. The MWD ranged from 1 to 3 mm with a mean of 2 mm for the N-Viro Soils (Table 6). This is higher than that of the four Ohio soils, which ranged from 0.73 mm for the sandy soil to 1.58 mm for the Kokomo silty clay loam. Aggregate stability is important when these materials are used in reclamation and for topsoil.

### Shrinkage

An important physical property of soils is its tendency to shrink when dried and to swell when wet. The volume percentage shrinkage of the N-Viro Soils ranged from 40 to 70%, with a mean of 58%, with one material exhibiting shrinkage of >100% (Table 7). We measured values of  $\approx 25$  to 30% for Ohio surface-horizon soils (Table 7). The high shrinkage capacity of these materials may be due to the hygroscopic nature of both the sludge organic matter and of the AA. Histosols have shrinkage values of 30 to 70% (Everett, 1983). Actual shrinkage in the field will not approach these values because most of the water in N-Viro Soil is held at high moisture tensions causing these materials to resist complete drying.

### Atterberg Limits

The Atterberg limits: liquid limit, plastic limit, and plasticity index are measures of the ability of a soil to be deformed across a range of moisture contents. The liquid limit is the gravimetric moisture content at which a soil will flow when subjected to a striking force. It is an indirect measure of the shear strength. The higher the moisture content at the liquid limit, the lower the potential of the soil to flow or slump under normal moisture conditions. The N-Viro Soils had liquid limits of 39 to 133% moisture by weight with an average of 76% (Table 7). Since the moisture content of the N-Viro Soils ranged from 25 to 55%, they would probably not slump under their normal moisture contents. This helps to explain why N-Viro Soil can be easily stacked. The plastic limit is the gravimetric moisture content of a soil at which it will begin to exhibit plastic behavior. The higher the moisture content at the plastic limit, the less plastic the soil will be at normal moisture contents. Several of the N-Viro Soils (3, 4, 5, 13, 16, and 24) were so low in plasticity that this test could not be performed. The plastic limit ranged from 46 to 105% moisture (Table 7), with a mean of 64%. Most of the N-Viro Soils would have moisture contents below the plastic limit and would not exhibit plastic behavior. This is important when transporting, spreading or bulldozing the material. The plasticity index, the range of moisture content over which the materials are plastic, and defined

Table 6. Aggregate stability and mean weight diameter in 28 N-Viro Soils and four selected mineral soils. Mean of duplicate analyses.

No.	Location	Mass fraction of total sample													
		>5 mm		5-2 mm		2-1 mm		1-0.5 mm		0.5-0.25 mm		<0.25 mm		MWD (mm)	
		Mean	RPD†	Mean	RPD†	Mean	RPD†	Mean	RPD†	Mean	RPD†	Mean	RPD†	Mean	RPD†
1	Aged Horsham, England	0.02	40.8	0.31	4.9	0.14	6.2	0.05	74.5	0.07	45.8	0.41	5.0	1.53	6.59
2	Bowling Green, KY	0.28	6.9	0.22	15.0	0.12	8.7	0.06	22.1	0.03	32.8	0.28	9.9	2.46	1.47
3	Aged Durham, NC	0.16	104.6	0.19	34.9	0.13	7.9	0.09	88.6	0.11	21.1	0.31	11.6	1.85	29.91
4	Durham, NC	0.15	9.9	0.16	35.6	0.17	2.3	0.17	5.9	0.07	50.2	0.28	7.4	1.74	13.99
5	Easley, SC	0.29	24.9	0.18	0.8	0.10	21.9	0.05	54.5	0.04	91.1	0.35	10.7	2.30	14.03
6	Toledo, OH (FGD)	0.32	8.0	0.20	8.3	0.10	5.9	0.07	53.9	0.06	78.5	0.25	2.2	2.54	2.74
7	Buckland, England	0.34	8.2	0.31	0.9	0.05	50.7	0.01	19.9	0.01	66.1	0.29	1.5	2.91	3.85
8	East Hyde, England	0.01	61.6	0.19	5.4	0.11	0.8	0.08	18.0	0.06	26.3	0.55	0.1	1.05	0.53
9	Horsham, England	0.01	23.2	0.29	2.5	0.13	5.1	0.05	60.3	0.07	43.2	0.45	4.1	1.38	2.48
10	Greenville, SC	0.26	9.4	0.21	7.3	0.11	1.1	0.07	6.6	0.03	44.7	0.32	7.8	2.29	3.03
11	Phillipsburg, NJ	0.20	17.8	0.29	9.3	0.14	1.5	0.06	73.9	0.06	71.4	0.26	0.4	2.31	2.60
12	Jeffersonville, IN	0.09	34.2	0.20	15.6	0.13	6.9	0.08	57.1	0.08	53.6	0.42	1.2	1.49	4.48
13	Kent County, DE	0.22	31.0	0.17	1.2	0.12	16.6	0.05	45.0	0.08	56.2	0.36	8.1	1.98	15.76
14	Knox County, TN	0.09	56.8	0.14	26.1	0.13	2.2	0.12	19.4	0.06	26.4	0.47	1.4	1.29	8.91
15	Lexington, KY	0.17	9.4	0.16	11.6	0.14	4.1	0.07	68.0	0.08	48.8	0.38	8.3	1.74	7.22
16	Clyde, NC	0.11	75.0	0.14	9.3	0.13	6.1	0.16	3.5	0.11	43.9	0.36	2.8	1.42	23.67
17	Toledo, OH (LKD)	0.27	26.1	0.22	5.8	0.16	5.6	0.07	88.1	0.04	35.9	0.23	11.1	2.47	13.72
18	Oakland, CA	0.22	35.4	0.16	0.1	0.10	28.9	0.06	86.8	0.05	39.7	0.41	4.4	1.93	16.17
19	Middlesex County, NJ	0.21	15.1	0.18	11.8	0.13	2.3	0.07	63.4	0.09	51.7	0.32	4.5	2.03	3.55
20	Sioux City, IA	0.23	4.5	0.19	12.6	0.12	3.6	0.10	5.6	0.05	35.5	0.31	5.6	2.15	5.86
21	St. Paul, MN	0.03	41.1	0.20	0.6	0.17	1.7	0.10	69.8	0.12	43.7	0.38	0.7	1.28	2.35
22	Sydney, Australia (Brown)	0.10	10.5	0.18	6.0	0.15	0.3	0.13	91.6	0.15	69.8	0.28	4.0	1.58	2.77
23	Sydney, Australia (Gray)	0.35	0.7	0.21	2.9	0.03	6.0	0.01	83.2	0.01	54.7	0.40	0.1	2.58	0.14
24	Tomball, TX	0.11	60.2	0.19	7.1	0.11	25.8	0.08	80.7	0.12	33.1	0.39	6.2	1.54	19.67
25	Troy, IL	0.24	17.4	0.19	1.2	0.11	2.8	0.08	15.0	0.04	17.6	0.34	11.2	2.18	9.46
26	Syracuse, NY	0.44	5.4	0.15	12.8	0.07	4.4	0.04	9.3	0.02	2.3	0.28	0.7	2.92	1.56
27	Jupiter, FL	0.35	18.3	0.30	17.0	0.08	3.5	0.02	2.7	0.03	18.4	0.22	2.4	3.00	4.50
28	Tarpon Springs, FL	0.17	11.7	0.17	12.7	0.12	11.1	0.12	1.2	0.07	12.9	0.35	10.6	1.80	8.63
	Overall mean	0.20		0.20		0.12		0.07		0.06		0.34		1.99	
	Overall SD	0.11		0.05		0.03		0.04		0.04		0.08		0.54	
	Hazleton sandy loam	0.03	-	0.05	-	0.09	-	0.15	-	0.31	-	0.37	-	0.73	-
	Kokomo silty clay loam	0.18	-	0.10	-	0.09	-	0.08	-	0.17	-	0.56	-	1.58	-
	Miamian silt loam	0.18	-	0.03	-	0.04	-	0.07	-	0.12	-	0.73	-	1.26	-
	Paulding clay	0.09	-	0.19	-	0.13	-	0.11	-	0.12	-	0.37	-	1.48	-

† Relative percent difference.

as the difference between the liquid and plastic limits, varied from 5 to 33% for the N-Viro Soils with an average of 18% (Table 7). The liquid limit of 76% for the N-Viro Soils was much higher than values for the Ohio mineral soils (Table 7); data were not shown for the sandy soil as these soils do not exhibit plastic behavior. Likewise, the plastic limit mean value of 64% for the N-Viro Soils is much higher than soil values (21-35%). Plasticity index values were similar, however, for N-Viro Soils and mineral soils. This may mean that N-Viro Soils and mineral soils have the same plastic behavior, but a large percentage of the moisture in N-Viro Soil, held in the smallest pores, do not contribute to their plastic behavior.

### Particle-Size Distribution

N-Viro Soils are well aggregated and particle sizes reflect this high structural aggregation. Most of the material, 56% on average, had particles >2 mm in diam. (Table 8). This compares with the 40% in water stable aggregates >2 mm (Table 6), meaning that >70% of the >2-mm particles were water stable. About 23% of the >2-mm fraction (13% of the total mass) was in the size range of 2 to 4.7 mm, and another 19% were particles between 6.35 and 16 mm. An average of 20% of the N-Viro Soils had water stable aggregates of 2 to 5 mm (Table 6), which is larger than the 13% in the 2- to

4.7-mm dry sieved fraction. This difference could be due to sample variability, number of samples in each test, differences in procedures and rounding errors, but suggests that a high percentage of this size particles are water stable.

Sieving of the <2-mm fraction showed that most of the material was in grain sizes of 1 to 2 mm and 0.5 to 1 mm (Table 9). About 8% was in the <0.25-mm fraction. This compares with >30% of wet sieved material in this same size fraction (Table 6), the additional fine particles coming from slaking of larger aggregates. Less than 1% of the <2-mm fraction was <0.05 mm, silt size or smaller. We were unable to disperse the N-Viro Soils in order to determine the content of clay-sized primary particles because of the high degree of aggregation of these materials, but we know from the nature of the AA and sludge that N-Viro Soils must contain large amounts of aggregated clay and silt sized particles. X-ray diffraction analysis revealed the presence of mica and kaolinite in the lime kiln dust used in the Toledo N-Viro Soil (no. 17). Highly aggregated particles such as are found in N-Viro Soil present a desirable environment for soil processes such as water retention, air permeability and structural stability.

The 28 N-Viro Soils were ranked by means for each physical parameter measured and the results used to evaluate the effects of N-Viro process parameters summa-

**Table 7. Atterberg limits and shrinkage in 28 N-Viro Soils and four selected mineral soils.**

No.	Location	Liquid limit	Plastic limit	Plasticity index	Shrinkage (%)	
		% moisture	% moisture	%	Mean	RPD†
1	Aged Horsham, England	75.61	62.90	12.71	40.33	3.52
2	Bowling Green, KY	87.53	76.35	11.18	73.50	13.42
3	Aged Durham, NC	38.99	—	—	37.89	12.20
4	Durham, NC	50.50	—	—	49.14	5.45
5	Easley, SC	89.28	—	—	51.90	7.62
6	Toledo, OH (FGD)	89.20	60.41	28.79	69.90	4.52
7	Buckland, England	74.39	55.40	18.99	42.42	11.78
8	East Hyde, England	73.80	58.21	15.59	55.77	24.89
9	Horsham, England	74.59	57.34	17.25	44.56	33.53
10	Greenville, SC	76.56	59.70	16.86	58.51	4.17
11	Phillipsburg, NJ	69.96	49.94	20.02	39.29	16.89
12	Jeffersonville, IN	69.80	46.18	23.62	58.85	1.19
13	Kent County, DE	57.57	—	—	—	—
14	Knox County, TN	56.89	48.01	8.88	44.42	17.29
15	Lexington, KY	112.39	104.64	7.75	77.24	8.95
16	Clyde, NC	46.50	—	—	55.05	13.01
17	Toledo, OH (LKD)	76.72	63.29	13.43	56.17	38.56
18	Oakland, CA	115.10	95.00	20.10	54.80	101.63
19	Middlesex County, NJ	85.98	56.78	29.20	42.85	3.60
20	Sioux City, IA	76.68	59.02	17.66	68.41	4.72
21	St. Paul, MN	73.08	57.44	15.64	57.88	6.96
22	Sydney, Australia (Brown)	65.90	60.53	5.37	55.67	14.24
23	Sydney, Australia (Gray)	133.33	100.09	33.24	103.01	18.64
24	Tomball, TX	49.68	—	—	32.74	—
25	Troy, IL	68.19	58.00	10.19	59.01	4.57
26	Syracuse, NY	93.92	62.45	31.47	67.73	5.26
27	Jupiter, FL	69.86	54.75	15.11	42.03	7.40
28	Tarpon Springs, FL	74.62	55.22	19.40	54.81	12.00
	Overall mean	75.95	63.71	17.84	58.12	—
	Overall SD	20.75	15.97	7.63	16.79	—
	Hazleton sandy loam	—	—	—	—	—
	Kokomo silty clay loam	40.70	23.60	17.10	26.40	—
	Miamian silt loam	31.20	20.90	110.30	26.60	—
	Paulding clay	54.90	35.00	19.90	29.70	—

† Relative percent difference.

rized in Table 1. N-Viro Soils 23, 18, 15, and 26 had the lowest solids content, and particle and bulk densities, while Materials 3, 24, and 13 were the highest. Materials 23, 18, and 15 had low to average AA dosages, but 26

had one of the highest. Materials 3 and 24 had low to medium dose rates, while 13 had one of the highest. On the other hand, Materials 3 and 24 were aged (a year or more of storage in the open). These rankings suggest

**Table 8. Whole sample particle size sieve analysis in 24 N-Viro Soils.**

No.	Location	Sieve size (mm)							
		>32	32-25.4	25.4-19	19-16	16-6.35	6.35-4.7	4.7-2	<2
		% by weight							
1	Aged Horsham, England	0.0	0.0	0.0	0.0	0.1	2.8	47.1	50.0
2	Bowling Green, KY	0.0	1.1	1.0	2.2	25.0	9.0	24.7	37.0
3	Aged Durham, NC	0.0	9.3	2.6	0.0	18.9	4.4	11.1	53.7
4	Durham, NC	0.0	0.0	0.0	2.2	25.3	4.7	17.8	50.1
5	Easley, SC	0.0	0.0	2.8	7.7	26.9	7.9	18.1	35.5
6	Toledo, OH (FGD)	0.0	0.0	0.0	3.4	34.2	13.2	24.7	24.5
7	Buckland, England	0.0	5.9	4.0	10.1	28.1	10.3	32.6	9.0
8	East Hyde, England	0.0	0.0	0.0	0.0	0.4	0.7	24.2	74.6
9	Horsham, England	0.0	0.0	0.0	0.0	0.0	0.3	43.1	56.6
10	Greenville, SC	0.0	0.0	0.0	0.0	20.2	5.4	14.7	59.7
11	Phillipsburg, NJ	0.0	0.0	2.9	0.6	42.2	10.0	22.9	21.4
12	Jeffersonville, IN	0.0	0.0	0.0	0.0	8.5	9.8	28.8	52.9
13	Kent County, DE	0.0	1.5	3.5	0.7	15.4	5.0	18.0	56.0
15	Lexington, KY	0.0	0.0	1.5	2.2	28.8	8.6	25.9	33.0
17	Toledo, OH (LKD)	0.0	0.0	0.0	0.0	20.9	16.7	34.8	27.7
18	Oakland, CA	0.0	0.0	18.9	0.0	27.7	11.8	17.2	24.3
19	Sayreville, NJ	0.0	0.0	0.0	0.0	8.4	4.2	22.8	64.6
20	Sioux City, IA	9.3	4.2	9.6	1.3	28.8	4.9	13.0	28.8
21	St. Paul, MN	0.0	0.0	0.0	0.0	0.2	3.1	22.5	74.2
22	Sydney, Australia (Brown)	0.0	39.2	0.0	0.0	5.5	3.0	11.7	40.5
24	Tomball, TX	0.0	0.0	0.0	0.0	12.4	5.0	18.2	64.4
25	Troy, IL	0.0	0.0	0.0	4.5	27.6	7.0	18.4	42.5
27	Jupiter, FL	0.0	0.0	0.0	0.0	27.5	17.5	31.2	23.8
28	Tarpon Springs, FL	0.0	0.7	1.2	1.5	10.1	5.4	19.2	61.9
	Overall mean	0.4	2.6	2.0	1.5	18.5	7.1	23.4	44.4
	Overall SD	1.9	8.1	4.2	2.6	12.1	4.5	9.2	18.0

Table 9. Particle-size Sieve Analysis of the &lt;2 mm fraction in 24 N-Viro Soils.

Np.	Location	Sieve size (mm)						
		2-1	1-0.5	0.5-0.25	0.25-0.1	0.1-0.074	0.074-0.05	<0.05
		% by weight						
1	Aged Horsham, England	40.6	53.5	4.9	0.7	0.2	0.0	0.0
2	Bowling Green, KY	37.9	36.6	13.5	10.0	1.3	0.1	0.1
3	Aged Durham, NC	23.1	23.3	12.6	21.8	6.6	9.5	3.2
4	Durham, NC	32.4	32.4	13.0	14.2	3.5	3.5	0.3
5	Easley, SC	36.4	39.6	14.4	15.1	3.7	0.4	0.1
6	Toledo, OH (FGD)	38.2	27.2	12.7	14.6	3.5	2.7	1.1
7	Buckland, England	87.0	12.5	0.6	0.1	0.0	0.0	0.0
8	East Hyde, England	25.5	61.3	11.5	1.5	0.2	0.1	0.1
9	Horsham, England	41.0	54.9	3.3	0.5	0.1	0.1	0.0
10	Greenville, SC	22.0	22.9	12.2	19.4	6.1	10.8	6.8
11	Phillipsburg, NJ	54.2	25.5	9.3	8.6	2.0	0.3	0.0
12	Jeffersonville, IN	29.8	36.0	26.8	6.3	0.4	0.1	0.0
13	Kent County, DE	24.2	18.0	13.0	30.7	8.0	5.7	0.2
15	Lexington, KY	37.8	52.5	9.1	0.4	0.1	0.0	0.0
17	Toledo, OH (LKD)	56.2	23.5	7.1	7.8	2.2	2.4	0.1
18	Oakland, CA	40.2	25.1	12.7	15.5	3.4	2.3	0.9
19	Sayreville, NJ	39.5	31.0	13.1	13.0	2.8	0.6	0.0
20	Sioux City, IA	36.6	29.1	13.8	15.3	3.9	1.0	0.1
21	St. Paul, MN	33.5	24.1	11.9	18.1	4.8	4.7	2.8
22	Sydney, Australia (Brown)	26.6	33.9	17.3	16.7	2.8	1.8	0.7
24	Tomball, TX	20.0	16.8	11.9	32.5	9.2	6.2	3.3
25	Troy, IL	36.9	21.4	9.6	15.8	5.6	8.7	1.7
27	Jupiter, FL	44.7	23.4	13.5	14.6	3.0	0.3	0.0
28	Tarpon Springs, FL	25.9	34.4	22.2	15.8	1.5	0.1	0.1
	Overall mean	37.1	31.6	12.1	12.9	3.1	2.6	0.9
	Overall SD	14.1	12.8	5.4	8.7	2.6	3.3	1.6

that solids content is due to a combination of AA dose rate and subsequent drying. Likewise densities increase as either the mineral component increases with AA dose rate, or organic matter content decreases with aging. Porosity was generally inversely ranked with solids content, the materials with higher dose rate or older having lower total porosities. Likewise, saturated water holding capacity, liquid and plastic limits and shrinkage were inversely ranked with solids content.

No other parameters exhibited any rank order relationship with AA dose or aging.

### Effects of N-Viro Soil on Physical Properties of Mineral Soil

Physical characteristics of the Columbus N-Viro Soil were in the range seen for the 28 materials in the characterization component of the study, with the exception of the 33 KPa moisture content (53% by volume for Columbus vs. a range of 25 to 41% for the 28 other N-Viro Soils), the <0.25-mm aggregate size (12% by weight for Columbus vs. a range of 22 to 55% for the 28 other N-Viro Soils), and the plastic limit (42% for Columbus vs. 46 to 105% for the 28 other N-Viro Soils; Table 10).

All effects of N-Viro Soil on soil physical properties were highly significant ( $P = 0.01$ ), except bulk density where the effect was significant ( $P = 0.05$ ), and total porosity, 33 KPa moisture holding capacity, 0.5- to 0.25-mm water stable aggregates, and pocket penetrometer measurements, which were not significant (Table 10). Total porosity is calculated from particle and bulk densities and is thus subject to error compounding; field pocket penetrometer measurements are highly variable and lack the precision of laboratory measurements.

Both particle and bulk densities decreased with N-Viro

Soil addition (Table 10). Total porosity showed a nonsignificant increase. While the 33 KPa moisture holding capacity did not increase significantly, the 1.5 MPa moisture content did.

All water stable aggregates >0.5 mm increased with N-Viro Soil addition, while there was a corresponding decrease in the dispersed fraction (<0.25 mm; Table 10). Only 47% of the control soil had water stable aggregates, compared with 88% for the treated soil.

There was a highly significant, fivefold increase in saturated hydraulic conductivity with N-Viro Soil (Table 10).

Both the liquid and plastic limits of the Miamian silt loam were significantly increased with the application of N-Viro Soil (Table 10). Given that the moisture holding capacity of the soil also increased, this change should have no net effect on the plastic behavior of the soil.

The penetrability of the soil as measured with a pocket penetrometer was not significantly changed with N-Viro Soil addition, although there was an increasing trend (Table 9). Improvement in the overall tilth of the soil could be observed when the plots were rototilled. It was difficult to till the control plots to more than a 10-cm depth, while the treated plots were easily tilled to the set depth of 15 cm.

A predicted value for each soil physical parameter was calculated by assuming that the changes observed were due only to a volumetric mixture of the control soil and the N-Viro Soil. The measured bulk density of N-Viro Soil (Table 10) and an assumed mixing depth of 15 cm were used to calculate the volume ratio. The predicted values were generally within 40% of the observed value. The largest deviation was for the <0.25-mm water stable aggregates in which the predicted value greatly over predicted the observed value. This is understandable since the increased Ca level in the soil with

**Table 10. Effects of N-Viro Soil on soil physical properties in the field.**

Property	N-Viro Soil		500 Mg/ha N-Viro Soil			Control		28 N-Viro Soils	
	Avg.	SD	Avg.	SD	Predicted	Avg.	SD	Avg.	SD
Solids fraction	0.56	0.01	0.78	0.03	0.71	0.86	0.01 nd†	0.62	0.08
Bulk density, Mg/m <sup>3</sup>	0.55	0.01	1.03	0.14	1.04	1.39	0.11*	0.59	0.11
Particle density, Mg/m <sup>3</sup>	2.09	0.01	2.23	0.08	2.33	2.57	0.03**	1.96	0.18
Porosity, %	73.73	—	53.00	6.00	58.60	44.00	5.80 ns	69.90	3.46
Moisture retention, v/v									
5.9 KPa	0.40	0.00	0.41	0.07	0.37	0.32	0.04	0.58	0.07
33 KPa	0.32	0.01	0.34	0.06	0.40	0.27	0.04 ns	0.34	0.04
1.5 MPa	0.22	0.00	0.20	0.01	0.27	0.15	0.01**	0.33	0.06
Available water	0.18	0.00	0.21	0.05	0.17	0.17	0.02**		
Aggregate stability, wt. fraction									
>5 mm	0.29	0.05	0.15	0.04	0.17	0.06	0.06**	0.20	0.11
5-2 mm	0.24	0.05	0.23	0.04	0.15	0.07	0.02**	0.20	0.05
2-1 mm	0.17	0.01	0.20	0.04	0.14	0.11	0.04**	0.12	0.03
1-0.5 mm	0.09	0.05	0.16	0.04	0.10	0.10	0.04**	0.07	0.04
0.5-0.25 mm	0.09	0.03	0.14	0.04	0.12	0.15	0.03**	0.06	0.04
<0.25 mm	0.12	0.03	0.17	0.06	0.33	0.53	0.10**	0.34	0.08
Saturated hydraulic conductivity, cm/s	0.0094	0.005	0.0041	0.0041	0.0050	0.0008	0.0006**	0.03	0.05
Atterberg limits, % water by wt.									
Liquid limit	65.01	—	30.79	1.87	43.45	22.71	0.75**	75.95	20.75
Plastic limit	41.93	1.57	31.20	2.06	32.53	23.49	4.06**	63.71	15.97
Penetrability, kg/cm <sup>2</sup>	—	—	0.50	0.07	—	1.51	1.01ns	—	—

\*, \*\*, ns = Significant at the 0.05 and 0.01 probability levels, respectively, and not significant; based on *t*-test.

† nd = not analyzed statistically.

N-Viro Soil may have flocculated control soil colloids, an effect not predicted by a simple mixture model. In almost all cases, the predicted values underestimated the effect of the N-Viro Soil, suggesting that physical, chemical, and biological reactions between N-Viro Soil and the control soil may have influenced the observed changes in soil physical properties over and above the volume weighted effect of the N-Viro Soil itself.

## DISCUSSION

This study of N-Viro Soil properties is the first comprehensive survey on the characteristics of these materials, and the data should be valuable to users of these products. In spite of a wide range in sludge types (primary, aerobic, anaerobic, and waste activated), AA type (CKD, LKD, fluidized bed ash, flyash, and lime), and dose rate (32 to 73% of cake solids), physical properties of the 28 N-Viro Soils in the survey were generally similar, with standard deviations in most cases <50% of the mean.

On average, the N-Viro Soils have the chemical characteristics of a high organic matter, saline, calcareous soil. Their physical properties are those of medium to fine textured, porous soils with granular, stable aggregates, and nonplastic consistency. The moisture retention characteristics are those of a fine textured soil dominated by fine pores and medium to high available water holding capacity, and these materials are highly permeable, even when compacted. While the particle and bulk densities appear to be simple mixture effects of the components, the content of large stable aggregates is a result of chemical interactions between the sludge and AA. These might include the formation of carbonate and silicate cements, particularly true of the cement kiln dusts, which undergo pozzolonic reactions, as well as stabilization of the sludge organic matter within the mineral matrix. The nonplastic behavior of the N-Viro Soils is probably due

to the formation of stable aggregates. Water retention characteristics are probably a combination of additive and interactive effects of the components in N-Viro Soils. Both sludge organic matter and AA materials hold large amounts of water at high suction pressures as a result of microporosity and hygroscopic reactions. At lower suction pressures, water retention is a result of aggregate formation.

The field study showed that almost all measured soil physical properties of a physically degraded mineral soil were improved by the one-time application of 500 Mg/ha N-Viro Soil. This application rate is in the range used for reclamation, urban soil amendments, and as a topsoil blend (Logan, 1992; Logan and Burnham, 1992). Measurements were made 1 yr after application, and it is not clear how long lasting the effects will be. Short-term improvements in soil physical properties from the application of organic amendments like manures, sewage sludge, and composts have been attributed to the organic amendments themselves and to the microbial production of humic substances. As the organics degrade, the effects diminish. N-Viro Soil only contains ≈ 12% organic C (Table 2), which corresponds to ≈ 20% organic matter. Using data from a previous laboratory incubation study of N-Viro Soil decomposition (Logan et al., 1989), it is estimated that 92% of the N-Viro Soil organic matter would have decomposed by the time that soil physical properties were evaluated. It is, therefore, concluded that many of the observed effects should persist until dissolution of the N-Viro Soil alkalinity and other weathering reactions have occurred, a period of years.

The physical characteristics of N-Viro Soils, when compared with their chemical characteristics, suggest that chemical rather than physical attributes are likely to limit the use of these materials as soil substitutes. While high initial pH and acid neutralizing capacity,

together with high soluble salt content place limitations on the use of N-Viro Soils as soil substitutes, there appear to be no limitations due to their physical properties, and the soil amendment study suggests that the physical properties of degraded soils can be significantly improved with high rates of application of these materials.

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